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ABSTRACT

PREDICT (Performance and Reliability Evaluation with Diverse Information Combination and Tracking) is a set of structured quantitative approaches for the evaluation of system performance based on multiple information sources. The methodology integrates diverse types and sources of information, and their associated uncertainties, to develop full distributions for performance metrics, such as reliability. The successful application of PREDICT has involved system performance assessment in automotive product development, aging nuclear weapons, and fatigued turbine jet engines. In each of these applications, complex physical, mechanical and materials processes affect performance, safety and reliability assessments. Processes also include the physical actions taken during manufacturing, quality control, inspections, assembly, etc. and the steps involved in product design, development and certification. In this paper, we will examine the various types of processes involved in the decision making leading to production in an automotive system reliability example. Analysis of these processes includes not only understanding their impact on performance and reliability, but also the uncertainties associated with them. The automotive example demonstrates some of the tools used in tackling the complex problem of understanding processes. While some tools and methods exist for understanding processes (man made and natural) and the uncertainties associated with them, many of the complex issues discussed are open for continued research efforts.

KEYWORDS

Uncertainty Characterization, Expert Judgment, Decision Making, Reliability Prediction, Design/Product Assurance

PREDICT: AN INFORMATION INTEGRATION METHODOLOGY

A methodology has been developed and applied which integrates all available information about a complex problem, phenomenon, or system. PREDICT (Performance and Reliability Evaluation with Diverse Information Combination and Tracking) is a set of structured quantitative approaches for the evaluation of system performance based on multiple information sources. The methodology integrates diverse types and sources of information, and their associated uncertainties, to develop full uncertainty distributions for performance metrics, such as reliability, that can aid decision making. Applications include predicting complex system performance, where test data are lacking or expensive to obtain, through the integration of expert judgment, historical data, computer/simulation model predictions, and any relevant test/experimental data. This methodology can be used at any time during product development, including at the concept and early design phases, prior to prototyping, testing, or production, and before costly design decisions are made. The methodology is particularly well suited for tracking estimated system performance, safety and reliability for systems under change (e.g. development, aging, fatigue). The power of this methodology has been celebrated with an R&D 100 Award, presented by R&D Magazine.

The successful applications of PREDICT have involved system performance assessment in automotive product development, aging nuclear weapons, and fatigued turbine jet engines. In each of these applications, complex physical, mechanical and materials processes affect performance, safety and reliability assessments. Processes also include the physical actions taken during manufacturing, quality control, inspections, assembly, etc. and the steps involved in product design, development and certification. The next section provides a brief examination of some of the various types of processes involved in the decision making leading to production and/or certification in the application areas. Analysis of these processes includes not only understanding their impact on performance, safety and reliability, but also the uncertainties associated with them.

The PREDICT methodology includes formal methods for eliciting expert knowledge and information found in Meyer & Booker (2001). They advocate representing the system or problem in terms of the community practices, and extensive documentation of the knowledge obtained and its use. The example section illustrates the use of a company's greatest resource—the expertise of its experienced technical staff—and how that knowledge can aid in the process of making product decisions and development before implementing expensive test programs. For more detailed description of the elicited information and its analysis, a more complete case study can be found in Booker et al. (2002). The section on updating illustrates the process of incorporating new information can be incorporated into a product/process design assurance program. New information includes the asking of *what if* questions to estimate impacts of decisions prior to taking action.

PROCESSES UNDER UNCERTAINTY

We begin by examining different kinds and levels of processes. There are two general classes:

- Actions by humans (e.g., make the decision to use a particular physical model, assemble parts of a subsystem, testing for leaks, performing quality control procedures, examine complex code output and reduce it to a single metric)
- Actions by nature (e.g., aging, energy transfer, crack growth).

While some physical models and codes exist to adequately describe phenomena in the latter class, many processes in the first class are not so easily modeled or even understood. The two categories can occur simultaneously, with various linkages between them. For example, nature grows a crack, and humans attempt to describe that through a physical model that has been coded for computation.

Processes can also be categorized by level. The process of assembling components of a system, is at a lower level. On a much broader scale, consider structuring a company's product/process design assurance program. Delphi Automotive Systems has developed such a program and is using it for performance and reliability analyses during product development. The process steps or elements of this program are designed to build reliability into the system in the first place, starting when the system is still in the concept phase of development. The structuring of these processes include activities that constitute the company's way of doing business.

Figure 1 is a coarse scratch net indicating examples of activities in this larger scale process program. Within each box are more detailed scratch nets of sub-activities that interrelate to each other and to other sub-activities in other boxes. The arrows represent the interrelationships (e.g., information flow) among the boxes and their contained sub-activities. A brief description of the boxes follows from Kerscher (1993):

- Review customer specifications that influence the proposed product design. This includes the initial structuring of the system—it's components and processes (e.g., assembly of parts, testing for leaks, quality control). - Perform reliability analysis, including developing reliability models such as the traditional "bathtub curve" for product lifetime prediction.
- Establishing and updating a test plan/ program for both components (parts) and processes in the product. Here a strategy is developed for determining where to devote future testing and analysis resources. This involves updating reliability estimates and uncertainties in light of new requirements and information
- Perform organized product development testing. Support process capability studies, which are organized development tests of the manufacturing process.
- Manage failure reporting and corrective actions.
- Facilitate phase reviews at transition points in the program. These reviews include the approvals of all stake holders.
- Coordinate analysis activities and information flow with suppliers/vendors.
- Achieve validation—develop a product that meets requirements and demonstrate its performance.

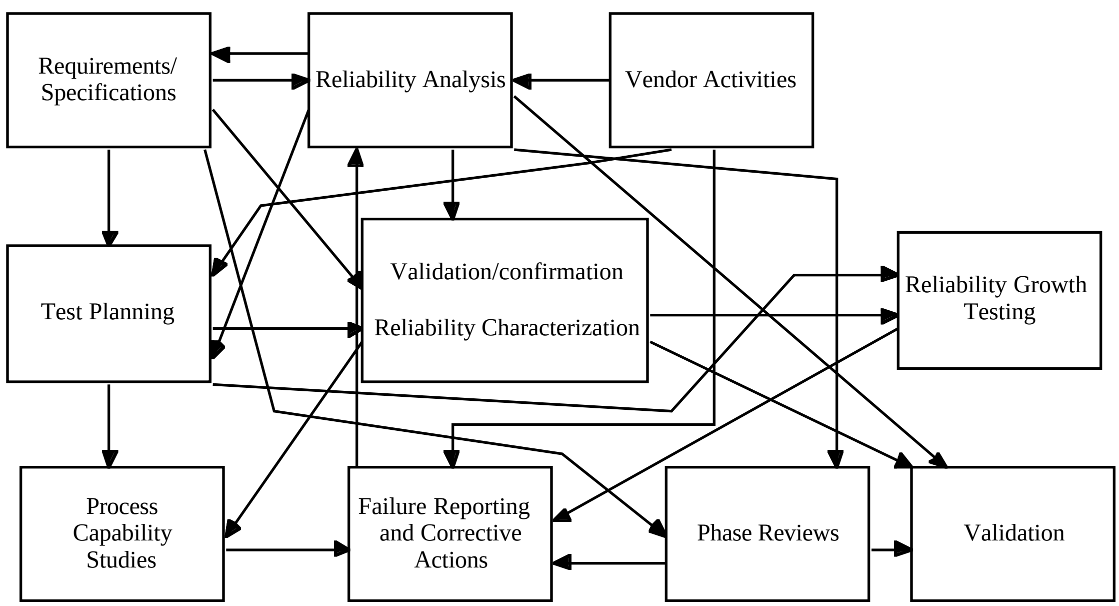

Figure 1: Scratch net of major activities in a product/process design assurance program

Providing a framework for understanding the information flow through these activities is a daunting task, but the example below illustrates how some of the flow can be understood using information integration analysis from the PREDICT methodology. Specifically, we will show how these activities are updated in a dynamic manner to reflect new information (including the uncertainty associated with it) as it becomes available. The information updating approaches (such as those based on Bayes Theorem) are directly applicable to this problem.

The following example illustrates how combining different information and different uncertainties aids in characterizing the reliability of a simple system. One of the challenging analysis issues associated with updating is how to quantify qualitative information from experts and its associated uncertainty. In addition to the traditional probability characterization of uncertainty, fuzzy logic and fuzzy set theory provide methods for tackling some the uncertainties that are qualitative in nature and originate from a lack of precise knowledge.

AN EXAMPLE OF THE RELIABILITY OF A SIMPLE SYSTEM

Consider a system (S) with three components (A, B, C) and one manufacturing process (MP), with all items operating in a series reliability arrangement, as shown in Figure 2. A and B constitute subsystem SS. Such an initial reliability logic flow diagram might be the result of a product team's activities in the Reliability Analysis box in Figure 1.

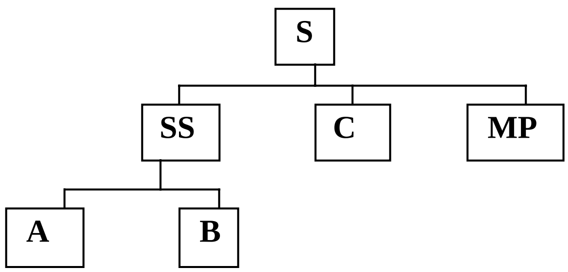

Figure 2: Simple system reliability logic flow diagram

The team might then decide, Kerscher et al. (2001), Kerscher et al. (2002), upon a two parameter Weibull model to model the reliability, representing both the components and the manufacturing process. The Weibull model not only gives an estimate of reliability (R), but it is also time (t) dependent, modeling the aging process:

$$R(t) = \exp\left(-\lambda \left(t^{\beta}\right)\right) \tag{1}$$

Using formal expert elicitation methods, Meyer & Booker (2001). the product team experts identify the values and uncertainties for the two parameters, β (the slope) and λ (the failure rate per scaled unit of time) for each component and process. These uncertainties are characterized by probability density functions and translate into uncertainties for the reliabilities. The uncertainty distribution for the system reliability (R_0) from the experts' knowledge is then calculated by multiplying the individual reliability uncertainty distributions using Monte Carlo simulation.

Upon examining the reliability uncertainty distribution for the system, the product team decided that improvements were necessary to make the reliability acceptable for all stake holders. The design team chose to redesign component C because it had the worst reliability, contributing the most to the over all poor system performance.

UPDATING WITHIN THE DESIGN ASSURANCE PROGRAM

The redesign of component C brings new information into the system and a new estimate of reliability is required. This kind of update is a simple replacement, new estimates for the redesign of C replacing the original ones. The left graph of Figure 3 shows the initial estimate of system reliability, (R_0), based on the experts original estimates and predicted using the Weibull model at t=36 months. The graph on the right of Figure 3 shows the first update with the redesign of C, (R_1). This update, R_1, exemplifies the interplay between requirements/specifications, reliability analysis, and reliability growth.

With the improvement in performance of C, attention of the design team focused on component B, which has a wide uncertainty. This team proposed to consider conducting a test for B to gain more information, reducing the uncertainty. Rather than performing the test, the team asked what would be the reduction in uncertainty if we performed 38 tests at 185,000 miles resulting in zero failures of B. Bayes theorem,

$$g(\theta|x) = [f(x|\theta)g(\theta)] / \int f(x|\theta)\, g(\theta)\, d\theta \tag{2}$$

can be used to update the expert judgement (serving as the prior, $g(\theta)$) for B with the proposed test result data (serving as the likelihood, $f(x|\theta)$). The left hand graph in Figure 4 shows the substantial (desired) reduction in uncertainty for this proposed test and its postulated result. This update, R_2, exemplifies the interplay between reliability analysis, test planning, and reliability growth.

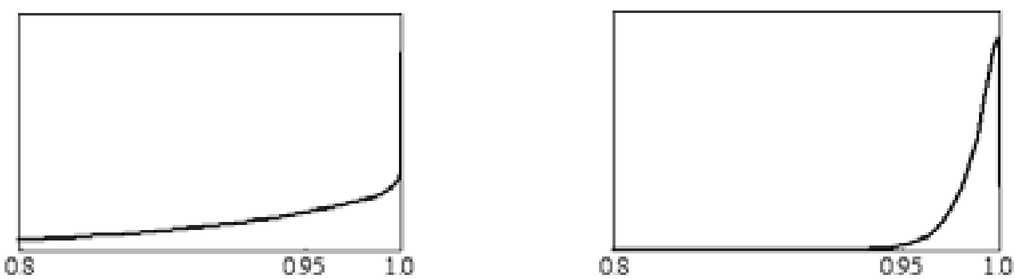

Figure 3: System reliability uncertainty distributions at 36 months for R_0 (left) and R_1 (right)

Before the test is performed for component B, the product team consults the supplier of component B to see if any additional information about its reliability can be obtained. However, the supplier's information is not in terms of the Weibull model. Instead, he has less than precise knowledge in the form of *if-then* rules that directly map his assessment of B into reliability. For example, *if* anticipated problems are very small, *then* the reliability is very good. Using fuzzy logic based membership functions, this linguistic information can be quantified, Smith et al. (1997), Ross et al. (2002). To update component B in light of the new information from the supplier, the question becomes how to combine the supplier's fuzzy generated reliability uncertainty distribution with the probability distribution function formulated from the team's prior information. It can be shown that Bayes Theorem is again useful in a theoretical sense for solving this problem because membership functions can be treated as likelihoods, Ross et al. (2002). Therefore, the new information from the supplier's rules and fuzzy membership functions can be used to form a likelihood distribution function for reliability that may be combined with the reliability distribution function provided by the team's prior information from R_0. The change in reliability of component B after this update (R_3) is similar to that of the previous update for the proposed 38 tests, as shown as the right side of Figure 4. This update, R_3, exemplifies the interplay between reliability analysis, working with the supplier, test planning, and reliability growth.

CONCLUSIONS AND FURTHER STUDIES

Characterizing the initial reliability, with large uncertainty, of a new product under development, and then working to reduce that uncertainty has been found to be a culturally acceptable way to address the reliability issue. The PREDICT methodology may prove useful in facilitating this approach. The methodology is flexible enough to integrate information at various stages of product development, including the asking of *what if* questions, such as in the R_2 update. As has been shown, updates of various types are possible, including information that is fuzzy in nature, such as in the R_3 update. If application of this methodology further assists a project team in successfully including the reliability issue earlier in its day to day activities involving performance, cost, and timeliness, while working within the uncertainties associated with a product/process design assurance program, it will prove to be a powerful additional tool in the development of a high reliability product. The whole idea is to allow new project development teams to effectively address the reliability issue at the start of the project with the same focus that they traditionally place on timing, resources and other issues.

The tools and methods discussed here are part of the PREDICT methodology for tackling the difficult problems of understanding and analyzing processes (man made and natural) and the uncertainties associated with them. Many of the complex issues associated with the uncertainties of processes (especially for the assurance program depicted in Figure 1) are open for continued research efforts. For example, alternative mathematical theories (e.g., fuzzy logic, possibility theory and evidence theory) may prove useful for capturing various kinds of uncertainty, especially if little is known about the process involved.

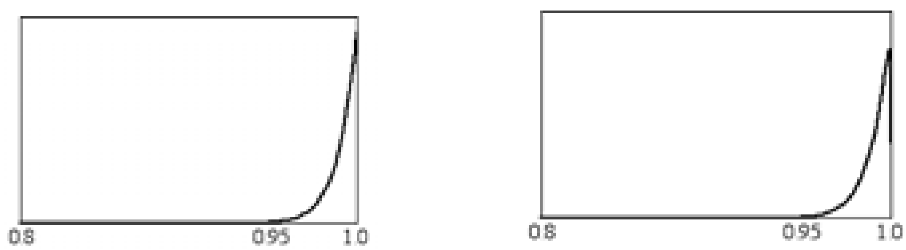

Figure 4: System reliability uncertainty distributions at 36 months for R_2 (left) and R_3(right)

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